



**Air Force Additive Manufacturing: Case Studies on Tools, Jigs, and Topology  
Optimization**

THESIS

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AIR FORCE ADDITIVE MANUFACTURING: CASE STUDIES ON TOOLS, JIGS,  
AND TOPOLOGY OPTIMIZATION

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William L. Page, BS

Captain, USAF

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### **Abstract**

This research explored the application of Additive Manufacturing (AM) to operations for various career fields using case study analysis to investigate to what degree can AM and topology optimization, a mathematical model to optimize the shape of a design, be utilized by various Air Force squadrons in everyday and contingency operations; to what degree can topology optimization be applied to the tools and jigs developed; and how much could topology optimization potentially save the Air Force over a given amount of time? These case studies evaluated nine tools and jigs for Explosive Ordnance Disposal and the Engineering Management Laboratory at the Air Force Institute of Technology. If deemed appropriate by the customer and designer, topology optimization was applied. As the hallmark of a good tool or jig is its usability, a survey was given to rate different aspects of usability for each case study. The scores were then used to identify trends between the case studies. Overall, this research found that AM and topology optimization could be applied to both daily and contingency operations, that topology optimization could be applied to various tools and jigs, and that the application of topology optimization could bring significant cost savings over time.

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# **AIR FORCE ADDITIVE MANUFACTURING: CASE STUDIES ON TOOLS, JIGS, AND TOPOLOGY OPTIMIZATION**

## **I. Introduction**

Additive Manufacturing (AM), also known as three-dimensional (3D) printing, has been recognized as a disruptive technology with great potential. A disruptive technology is anything that can create new job markets (Campbell, Bourell, & Gibson, 2012; Lipson, 2013). AM not only has this ability, but it also has the potential to completely change how goods are manufactured around the world. Additionally, the use of low-cost AM machines skyrocketed from 355 in 2008 to over 72,500 in 2013 (Campbell et al., 2012), showing a surge of availability to wider audiences and users. The explosive use of AM may be an indicator of a rising capability in the manufacturing industry worth investigating for Air Force operations. At the time of writing this thesis, not much research has been accomplished on end-use AM parts for applications in the Air Force. The limited research accomplished to date includes a user-centered design study of some tools and jigs for use by civil engineering operations (Shields, 2016) and some research on the use of AM for rocket parts (Gruss, 2015). The research accomplished has not focused on the use of topology optimization on specific parts/designs. Topology optimization is a mathematical method of optimizing the surface area and structure of design parts, which can be applied to AM to optimize the prints' strength and minimize the amount of material used. This research investigated the use of AM and topology optimization for end-use parts for Air Force operations.

## **Background**

AM is the production of items constructed layer by layer through various means and technologies. Three of the main technologies used in AM are powder bed fusion, fused filament fabrication, and material jetting (Gibson, Rosen, & Stucker, 2010; Hod Lipson, 2013). Powder bed fusion places a layer of plastic powder across the entire build space and then uses various techniques such as heat, ultraviolet light, or a liquid solution to harden specific sections of the powder which will become the final print. The remainder of the powder then acts as a support for the next layer. Fiber filament fabrication heats a line of plastic to near melting and then lays down the material one layer at a time as specified in the design file. Lastly, material jetting utilizes many nozzles that span across the length of the build space, and lays down either plastic or wax support material as needed and specified in the design file (Gibson et al., 2010).

AM was first known as rapid prototyping, and it was utilized by manufacturers to quickly develop multiple prototypes for various parts to test for ergonomics, aesthetics, and ease of manufacture. AM was later incorporated to create end-use parts in various fields such as construction, medicine, and fashion. As stated previously, the use of low-cost AM machines has exponentially increased over the last decade (Gibson et al., 2010). This dramatic increase warrants further research for military, specifically Air Force, applications. Such applications could include various tools and jigs. A tool is defined as an object that does work, such as screwdriver or a hammer. A jig is an object that helps a tool accomplish its work, such as a bracket for attaching multiple sensors to a robot like the one Shields designed (Pham & de Sam Lazaro, 1990; Shields, 2016). Topology optimization, in conjunction with AM, could provide a substantial benefit to the military,

as it saves money and material, which has grown in importance in the last few years of financial austerity. Topology optimization is a method through either hand calculations, which is extremely time consuming, or various computer programs, which calculates the optimal strength of the part while reducing the amount of material used given a specific load case (Brckett, Ashcroft, & Hague, 2011; Lei, Moon, & Bi, 2014).

AM is a growing technology with many unexplored applications. Some limitations that exist are the constraints of the current technology—such as the speed of the print, the materials available for use, the strength of the materials, the size of the part, and the imagination of the designer. The United States (U.S.) Navy, Army, and Marines have already accomplished research in the use of AM in operational environments, with little being completed by the US Air Force (Appleton, 2014; Kobryn, Ontko, Perkins, & Tiley, 2006; National Research Council, 2009; Shields, 2016). The Air Force could benefit greatly from further research into AM, due to dynamic operational environments and aging infrastructure and inventory, which require parts no longer manufactured or long lead times to acquire.

The current state of AM is one of growth; the use of low-cost AM machines has increased exponentially due to the expiration of several key patents. Despite the many types of printing that exist, each is only able to print one type of material at a time with few exceptions. There are some machines that are capable of adding material such as Kevlar or carbon fiber, but the majority of printers are only capable of printing solely in plastic or metal powder (Gibson et al., 2010; Hod Lipson, 2013). AM is currently used in the mass manufacturing industry to rapidly produce prototype products to test for several attributes including, but not limited to, ease of manufacture and aesthetics (Bechthold et

al., 2015; Campbell et al., 2012; Chiou, 2015; Hod Lipson, 2013; Moye, 2016). AM also expanded into other industries to include medical, construction and defense (Appleton, 2014; Gross; Erkal; Lockwood, 2014; Lim et al., 2012; Shields, 2016). Some research has been conducted on utilizing topology optimization for end-use AM parts. The research conducted has been focused on commercial parts and minimizing materials used to save money. however, nothing has been done with topology optimization for military parts (Brackett et al., 2011; Lei et al., 2014). Application in a military setting is different due to the logistical train that accompanies operations in contingency environments. Replacement parts, or even additional printing material, can take weeks if not longer to arrive in theater. Applying topology optimization to military operations can decrease the volume and frequency of resupplying these materials.

### **Problem to be Investigated**

This thesis investigated whether applications of AM and topology optimization are possible for application to Air Force operations. Military environments demand rugged equipment capable of performing multiple roles to save weight and time for the Soldier, Sailor, Marine, or Airman using it. These provide challenges for not only AM parts, but mass-manufactured products as well. This study investigated whether or not AM has a place in Air Force operations. Sub questions to this main idea that will also be investigated are to what degree can both AM and topology optimization be integrated into day-to-day U.S. Air Force operations. The specific research questions to this thesis is to what degree can AM and topology optimization be utilized by the various Air Force squadrons in their day-to-day and contingency operations, based on the current state of

technology; to what degree can topology optimization be included into the tools and jigs developed for Air Force Operations; and how much could topology optimization potentially save the Air Force over a given amount of time?

## **Methodology**

This study furthered the research accomplished in Capt Shields' thesis (2016). This thesis effort designed, printed, and tested nine tools and jigs in different case studies for various organizations to include the 788<sup>th</sup> EOD Flight, the Air Force Civil Engineer Center (AFCEC), and the Graduate School of Engineering and Management Laboratories at AFIT. The tools and jigs were then evaluated through a user-centered survey on usability. The design and testing of these items incorporated user-centered design survey methods as well as topology optimization methods where applicable.

The author utilized the Spiral Method of design to further the research accomplished by Shields (2016) to produce several different tools and jigs. The different case studies are summarized in Table 1. User-centered design surveys then evaluated the versatility and overall satisfaction with the tools and jigs developed. JMP, a statistical software package, then determined relationships between the questions and responses. Additionally, two of the jigs, the shaped charges, were tested to see how well they mimicked the explosive cuts made by the originals. Lastly, the results of each case study were evaluated for trends and lessons learned for broader applications.



Table 1. Case Studies and Descriptions

Case Study	Part Name	Description	Tool or Jig
1	Linear Shaped Charge	Mk 7 mod 8 linear shaped charge container	Jig
2	Conical Shaped Charge	Conically Shaped container for shaped charges	Jig
3	Omni-Directional Shaped Charge Carrier System	Jig designed to carry up to six omnidirectional shaped charges	Jig
4	“Blue Devil” Detonation Cord Connector	Jig used to join multiple pieces of detonation cord together	Jig
5	Non-metallic Probe	Long, thin probe meant to aid detecting buried explosive devices	Tool
6	Respirator Bottle Holder	Scalable support system to hold up to nine respirator bottles in place during experiments	Jig
7	Cuvette Holder	Cuvette support stand for spectrometer experiments	Jig
8	Gas Purifier Stands	Vertical support stands to aid experiments; includes nuts and bolts	Jig
9	Aerosol Nozzle	Printed aerosol nozzle for a UAV	Tool

A ProJet 3500 HDMAX printer and oven from 3DS were used to produce the parts for this study. This machine was a material jetting printer, which used bottles with various colors of plastics and a wax support material for the prints. The oven then melted the wax off each print in what is known as post processing.

### **Assumptions and Limitations**

Several assumptions were made throughout the course of this study. The first assumption is that time for the part to print was not a relative factor, due to the large

amount of time it takes for each print to conclude because of the long print time for some of the cases. The larger prints in the different case study printed in approximately 29 hours. While this is much faster than waiting for a part from the U.S., it may not necessarily meet the needs of an emergent situation. As the technology improves, the time it takes for a printer to complete a print will decrease. It was assumed that personnel in contingency environments would eventually have access to a AM machine at some point. This assumption was based on discussions with a subject matter expert from the Air Force Civil Engineer Center (AFCEC), who explained that the goal was to purchase AM machines for every Explosive Ordnance Disposal (EOD) flight in the US Air Force. Additionally, it was assumed that the material needed for the designs researched would be plastic. The Air Force Institute of Technology (AFIT) recently purchased an AM machine capable of printing parts comprised of metal powder; however, access to that printer was not available in the time required for this research.

## **II. Literature Review**

Additive Manufacturing (AM) is a recent technology making waves in many industries. The introduction of this new manufacturing method has created new markets and additionally, can create even more. AM has thus been rightly dubbed as a disruptive technology. AM has matured over the years—especially after the recent expiration of several key patents, which hastened technology diffusion and lead to a meteoric rise in low-cost machines climbing from 355 in 2008 to 72503 in 2013 (Gibson et al., 2010). All branches of the United States Armed Forces have conducted research on uses for AM (Funds et al., 2015; Shields, 2016).

### **Key Term Definition and Current State of Additive Manufacturing**

Various industries have investigated diverse applications of AM is and explored multiple facets of what it can do. AM has near limitless applications but is hampered by current technological constraints. One such limitation is the ability to print using multiple materials in the same part. The ability to print multiple materials, or even different types of plastic in the same job, will enable even greater flexibility in design and further push the limits of AM to only the designer's imagination. Additionally, the build space available for the prints is largely defined by the size of the printer available, and was relatively small.

While the ability to print in extremely small detail is a huge boon to several industries, the size of the available build space limits most other industries, such as aerospace and medical (Gibson et al., 2010; Lipson, 2013). The requirement to have

build spaces of this size is due to the specific requirements of the materials used in the printers. Plastic, for example, requires relatively warm and dry conditions for the best prints (Gibson et al., 2010; Lipson, 2013). Having an open build space could impact the plastic negatively by introducing more temperature variables. These fluctuations could produce variations in the curing time and strength of the material, which negate the benefit of uniform prints (Gibson et al., 2010; Lipson, 2013). The size limitations listed above impacted this research by placing an upper limit on the size of the designs as well as limiting the placement and orientation of the prints on the build space.

Another limitation that exists AM is the time for each print. Unlike the replicators in Star Trek, which produced an end-use product in seconds, current technology in AM makes each print relatively slow (Lipson, 2013). However, compared to the traditional manufacturing and shipping methods, this is a significant improvement.

The main AM processes at the time of this research include Vat Photopolymerization, Powder Bed Fusion, Material Extrusion, Material Jetting, Binder Jetting, Sheet Lamination, and Directed Energy Deposition (Gibson et al., 2010; Lipson, 2013). They all have different methods of construction and unique strengths and weaknesses. Let us look at a few of these processes in depth for example, specifically Powder Bed Fusion, Material Extrusion, and Material Jetting.

Powder Bed Fusion assembles each print by placing a layer of plastic/metal powder across the entire area of the print and then uses a medium such as ultraviolet light or a liquid solution to fuse the parts of the print together in that layer. The unused powder in that layer is used as a support material for the next layers. This process is then

repeated until the print is completed. The excess powder is then removed in post-processing and can be recycled for another print (Gibson et al., 2010; Lipson, 2013).

Material Extrusion heats a spool of plastic to near the melting point and then extrudes that plastic through a nozzle that traverses across the build space and onto a platform. The platform drops once that layer is completed, and the nozzle then travels across the build space once again laying down the next layer of plastic. Once the entire process is complete, the print can be removed from the printer and post-processing begins. Post-processing for this method may include removing excess plastic that was used to form a bridge between separate sections of the print to support the printing process (Gibson et al., 2010; Lipson, 2013).

Material Jetting printers utilize multiple nozzles that spread across the entire length of the build space to lay down one layer of either plastic or wax support material as necessary. This process is repeated until the part is complete, and post-processing can be started. Post-processing for this method involves melting the wax support material off the print using a specialized oven. These three methods of AM are used in every low-cost AM machine and provide the basis for the entire 3D printing revolution (Gibson et al., 2010; Lipson, 2013).

There are several different types of materials available for use in AM. The most prevalent material used is plastic (Gibson et al., 2010; Lipson, 2013). Other materials have been rising in use over the last few years as the technology has matured, specifically food, metal powder, “living ink” (described later), and concrete to name a few (Lipson, 2013). There are limitations with the current state of technology regarding the materials that can be used, as well as only being able to print one type of material at a time.

Topology optimization can increase the effectiveness of the materials by maximizing the strength of the print, while minimizing the amount of materials utilized per part (Bechthold et al., 2015; Brackett et al., 2011; Campbell et al., 2012; Gibson et al., 2010; Gross, Erkal, Lockwood, Chen, & Spence, 2014; Hod Lipson, 2013; Lei et al., 2014; Lim et al., 2012). By reducing the amount of material used, it can also provide a better tool or jig which optimizes its shape. Additionally, it can produce parts that are organic and aesthetically appealing.

Topology optimization, a mathematical strength-analysis method, is a great tool for use in responsible manufacturing. As stated in the previous paragraph, topology optimization has the power to preserve the strength of the printed part based on applied loads while minimizing the amount of materials used. This reduces the environmental impact of manufacturing both in the large- and small-scale industries, especially when coupled with other green initiatives such as the Design for Environment (Chiou, 2015; Gibson et al., 2010; Lipson, 2013). Several computer programs capable of applying topology optimization are currently available, such as Abaqus and SolidThinking Inspire.

Tools and jigs are ubiquitous across the world to help accomplish varying tasks. A tool is defined by Dictionary.com as “an implement, especially one held in the hand ... for performing or facilitating mechanical operations” or “anything used as a means of accomplishing a task or purpose” (<http://www.dictionary.com/browse/tool?s=t>). A jig is defined by the same website as “a plate, box, or open frame for holding work and for guiding a machine tool to the work, used especially for locating and spacing drilled holes; fixture” (<http://www.dictionary.com/browse/jig?s=t>).

## **Additive Manufacturing in the Manufacturing Industry**

While AM may not seem like a method utilized by the traditional manufacturing industry, this is exactly where it took off. AM started in the traditional manufacturing industry as a method of rapid prototyping, where companies would churn out several different prototypes of a new product to test various aspects of the design such as ergonomics, aesthetics, and ability to mass manufacture. The large-scale manufacturing industry still uses this method; however, not everything is accomplished in-house now. Companies are now able to contract out new designs to small-scale companies, which specialize in AM, to produce new parts much faster and with less expense than they could otherwise accomplish themselves.

The literature reviewed addressed several more applications for large-scale implementation to include printing large pieces of cars, planes, etc., prior to final assembly (Gibson et al., 2010; Lipson, 2013). The possibility exists to print the entire machine if the printer has sufficient definition to print the smaller pieces in the correct placement, the printer is large enough, print environment conditions are appropriate, and the infrastructure to support the print and post-processing is in place. Other large-scale applications include rapid manufacturing of specialized or customized pieces and parts. Having a core file with the ability to make customizations and add/remove sections for unique purposes and tasks is a unique benefit provided by the growth of AM. Small-scale companies can also make use of rapid manufacturing to their economic benefit (Gibson et al., 2010; Lipson, 2013).

The emergence of more low-cost AM machines has created new markets that enable small-scale companies to specialize in 3D printing. Small businesses can exploit

rapid prototyping and mass customization to make a profit and expand these new markets. The technological constraints, and lack of AM knowledge by the general population, currently push these companies into niche markets; however, awareness of AM and the ever-increasing capabilities are pushing the markets more into the spotlight and creating new jobs and career opportunities (Bechthold et al., 2015; Campbell et al., 2012; Gibson et al., 2010; Lipson, 2013).

### **Additive Manufacturing in the Medical Industry**

The medical industry has found numerous applications for AM. One such application is the construction of scaffolds for new organs and appendages. The scaffold creates the form for the new part and can then be implanted into the patient, where skin grows around the area (Gross et al., 2014; Lipson, 2013). This technique has applications for trauma patients or injured troops, who have lost ears, noses, etc., and require cosmetic surgery. The highly-customizable nature of AM lends itself to this area, so the new parts can perfectly mimic the ones lost. Current medical technologies, such as CT scanners and MRIs, have the ability to convert their images into .STL (or stereolithography) files, which are used to print the scaffolds (Gross et al., 2014; Lipson, 2013).

The medical industry has also applied AM to create autogenous bones for bone grafts, as well as printing soft tissue (Gross et al., 2014; Lipson, 2013). The bone grafts and soft tissue prints can be used for the same reasons as those listed in the above paragraph. The soft tissues also have the potential to help educate students at all levels and help prepare surgeons for surgical procedures. Schools and universities would no longer have to wait for cadavers to be donated or purchase animal organs for study if they



had access to machines capable of printing soft tissue. Furthermore, surgeons could print not only troublesome organs and growths, but they could also set up an entire limb or torso to create an extremely detailed and accurate training tool. This application can help medical professionals prepare for difficult or even rudimentary procedures to remain current, and help save lives (Gross et al., 2014; Lipson, 2013).

Future research could lead to even greater medical breakthroughs. Material research could create bones that are almost impossible to break (Lipson, 2013). Adding topology optimization could reduce the amount of material used in said bones to create hollow bones which could potentially help protect vital arteries. Further research into soft tissues could reduce, and eventually eliminate, the need for organ donors; doctors could print a replacement organ or muscle made from the same genetic material as the individual patient (Lipson, 2013).

### **Additive Manufacturing in the Construction Industry**

Additive Manufacturing has also made an impact in the construction industry. There are three types of AM used in construction: D-Shape, Concrete Printing, and Contour Crafting (Lim et al., 2012). D-Shape is very similar to powder bed fusion because it uses layers of powder and a bonding method, in this case, a chlorine-based liquid, to create a shape. The only difference between the two is the scale of the print.

Concrete printing is analogous to material extrusion because it uses a gantry with a nozzle to spread a specialized concrete blend to construct a structure layer-by-layer (Lim et al., 2012). Contour Crafting also uses an extrusion method to create a structure.

Contour Crafting, similar to material extrusion, employs a second material to support horizontal elements of the print (Lim et al., 2012).

There are several limitations existing for each of these methods. These methods require a large amount of time to complete, which may be detrimental to the build, if the weather changes for the worse. As such, these methods have only been accomplished in environmentally-controlled buildings, at the time of this paper. Additionally, the amount of material necessary for D-Shape potentially could be restrictive in remote and/or contingency environments. The time between layer placement in both Contour Crafting and Concrete Printing could possibly create cold joints in the structure—thus lowering the overall structure strength. Another downside, as well as potential benefit, is the aesthetic of the structure. Concrete Printing uses large layers, which could be perceived as aesthetically unappealing (Lim et al., 2012). However, it could also be a benefit if there were a second machine on the overhead support structure that could layer pieces of rebar and weld the next layer to the previous layer before the nozzle comes around for the next pass. This could increase the overall building strength by adding vertical reinforcement to the structure.

While there are limitations to the above methods, there are potential benefits to both public and private sector construction. Concrete structures, utilizing concrete printing, could be constructed using fewer personnel and completed in possibly less time than the traditional method. This application could place fewer people in potential danger while constructing structures that are more resistant to small-arms fire in a contingency environment. The reduction in manpower could lead to greater savings and profits from less overhead and personnel costs. Another potential benefit for Contour

Crafting and D-Shape is the aesthetics. These methods could produce unique, organic structures, which may be a large selling point in the private sector, as well as produce structures that are much harder to distinguish from enemy aerial surveillance for the military (Lim et al., 2012).

### **Additive Manufacturing in the United States Armed Forces**

The United States military has conducted research on service-specific applications of AM. Appleton (2014) listed potential solutions for the United States Marine Corps, which could also apply to all the other services: inventory, transportation, and obsolescence. For the purposes of this paper, inventory and transportation will be lumped together into an overall “logistics” category. Zimmerman and Allen (2013) also investigated logistics in their research regarding the impact of AM on logistics for the Army. Appleton (2014) and Zimmerman and Allen (2013) all hypothesized that incorporating AM could reduce the logistical chain in contingency environments; Zimmerman and Allen (2013) specifically found that AM could reduce resupply times for spare parts by 56% to 63% on average. This could easily be applied to the logistics of the other branches as well (Appleton, 2014; Zimmerman & Allen, 2013).

The United States Army has incorporated AM into operations in Afghanistan (Zimmerman & Allen, 2013). Rapid Equipping Teams set up mobile labs throughout Afghanistan, which were then able to address applications to problems sent to them by soldiers across the theater. Specifically, they were able to create an adapter to charge batteries the soldiers had to carry on patrols—saving weight and increasing morale (Zimmerman & Allen, 2013). Additionally, a research team from the U.S. Army

Armament Research, Development and Engineering Center (ARDEC) was able to additively manufacture an entire grenade launcher, the Rapid Additively Manufactured Ballistics Ordnance (RAMBO), and most of the accompanying round (Burns & Zunino, 2017). The ARDEC researchers were able to print the entirety of the launcher on a single build plate in only 35 hours, and the launch velocities of the rounds only differed from the original rounds by only 5% (Burns & Zunino, 2017). The work of Burns and Zunino (2017) show that a new world of rapid prototyping is dawning. Also, replacing the RAMBO in a contingency environment could be much faster than traditional resupply methods if a metal printer is located at one the Rapid Equipping Teams identified by Zimmerman and Allen (2013).

The United States Navy has added AM into their Fleet Repair Centers. These centers are able to create the necessary parts much faster than procuring a new one through the traditional methods of contracting a company to make a new one, or intensive labor at their centers (Appleton, 2014). Other military branches could incorporate AM in similar fashion to quickly produce replacement parts that could otherwise keep vehicles out of commission, due to long logistics chains, if the parts are unavailable by printing them on the spot. This again ties into the research accomplished by Zimmerman and Allen (2013).

The United States Air Force has accomplished research on multiple facets of AM to include aerospace alloys, aircraft structures, rocket parts, and tools and jigs (Funds et al., 2015; Kobryn et al., 2006; Shields, 2016). The Air Force Research Laboratory conducted research using AM for aerospace alloys and aircraft structures, and researchers took into account material strength, the current state of the technology, certification of

aircraft using AM, etc. (Kobryn et al., 2006). Shields (2016) directed research on developing several tools and jigs for use in Air Force Civil Engineer operations, which include a bracket to hold various sensors for an Explosive Ordnance Disposal robot.

### **Additive Manufacturing and Topology Optimization**

Applying topology optimization to AM has the potential to tremendously impact the future of the manufacturing industry. As green building and manufacturing practices are gaining traction in industry, it is a logical step forward to apply topology optimization to AM printed parts to reduce the amount of material used. Topology optimization applies one of several available methods to determine the optimal topology of a shape. The available methods include homogenization, solid isotropic material with penalization (SIMP), and bi- directional evolutionary structural optimization (BESO) (Brackett et al., 2011). Applying these methods can produce complex shapes, which make it a perfect candidate for AM.

Complexity adds cost in traditional manufacturing; however, complexity adds no cost whatsoever in AM as the cost for the print will be the same regardless (Bechthold et al., 2015; Brackett et al., 2011; Gibson et al., 2010; Lipson, 2013). Complexity in traditional manufacturing requires more pieces—thus more molds and more equipment and personnel costs. In reference to other research conducted for the military, no one has mentioned the use of AM with topology optimization. Applying topology optimization to AM for the military further improves the logistics challenge, by reducing the amount of material needed to transport and increasing the time between shipments.

### **III. Methodology**

Additive manufacturing has the potential to create nearly infinite possibilities for end-use products. As such, several design methods exist to facilitate and define the design process, such as the Spiral and “Vee” models. This thesis utilized the Spiral Model for design to develop end-use tools and jigs for EOD and the AFIT Laboratory. Each design effort was handled as an individual case study with a usability survey to first measure the usefulness of the tool/jig, and secondly, to identify trends between the case studies for overarching themes of applying AM and topology optimization to Air Force operations.

#### **Theory**

##### ***Case Studies***

The case study model was chosen as the primary methodology due to the general analytical generalization of the research questions (Gable, 1994; Yin, 2009). Additionally, the usability surveys were incorporated because usability is what defines a good tool or jig, as well as the synergy that can be gained from the marriage of case studies and surveys (Gable, 1994). Each of the nine design efforts researched in this thesis was investigated as an individual case study. Usability data was gathered through user-centered design surveys. Once all the data was received, descriptive statistics were run on each case study to determine the maximum, minimum, and median values in addition to the standard deviation for each of the separate areas of usability. The questions that correspond to each area of usability are sorted together to analyze the

descriptive statistics. Therefore, if there are three questions for one area, such of efficiency, and two respondents, there would be a total of six data points for that area. For each survey, there were three questions for quality, four for effectiveness, three for efficiency, one for safety, three for utility, three for learnability, two for memorability, and two questions for topology optimization; there was also a question reserved for comments. This led to a total of 20 data points for descriptive statistics for each survey, assuming all questions were answered. The descriptive statistics provide a snapshot of the tool or jig in the eyes of the customer; they also enable a trend analysis to be accomplished between the individual case studies. Table 2 below shows the nine case studies to include a brief description and if it is a tool or jig.

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Table 2. Case Studies, Descriptions, and Customers

Case Study	Part Name	Description	Tool or Jig	Topology Optimization Applied	Customer
1	Linear Shaped Charge	Mk 7 mod 8 linear shaped charge container	Jig	No	EOD
2	Conical Shaped Charge	Conically Shaped container for shaped charges	Jig	No	EOD
3	Omni-Directional Shaped Charge Carrier System	Jig designed to carry up to six omnidirectional shaped charges	Jig	Yes	AFCEC/ EOD
4	“Blue Devil” Detonation Cord Connector	Jig used to join multiple pieces of detonation cord together	Jig	No	EOD
5	Non-metallic Probe	Long, thin probe meant to aid detecting buried explosive devices	Tool	No	EOD
6	Respirator Bottle Holder	Scalable support system to hold up to nine respirator bottles in place during experiments	Jig	No	AFIT Labs
7	Cuvette Holder	Cuvette support stand for spectrometer experiments	Jig	Yes	AFIT Labs
8	Gas Purifier Stands	Vertical support stands to aid experiments; includes nuts and bolts	Jig	Yes	AFIT Labs
9	Aerosol Nozzle	Printed aerosol nozzle for a UAV	Tool	No	AFIT Labs



### ***Spiral Method***

As stated in the previous chapter, the Spiral Model can be applied to the design of additively-manufactured tools and jigs. Shields (2016) applied the Spiral Model in his research and since this work is a continuation of his research, the logical conclusion was to exploit the same model and method of data collection. Figure 1 is a visual representation of the Spiral Model as shown in Shields' (2016) work and noted by Nielson (1993).

The Spiral Process Model is comparable to other iterative/evolutionary design methods, such as the “Vee” and waterfall methods—but with the additional component of risk analysis and the prescribed use of prototypes (Mohammed, Munassar, & Govardhan, 2010). The risk analysis, and use of prototypes, allows for a truly iterative design process and permits the addition of topology optimization towards the later designs to cut material and production cost per unit. Overall, the Spiral Method has four distinctive sectors: objective setting, risk assessment and reduction, development and validation, and planning. These sectors are applied at different phases of the project life-cycle (Mohammed et al., 2010).

Each individual phase starts with an internal review of design requirements and overall product needs, also known as objective setting. This stage defines the overall objectives of the current design phase and the requirements of the product. Once these objectives are set, the spiral then moves to the next sector—risk assessment and reduction (Mohammed et al., 2010).

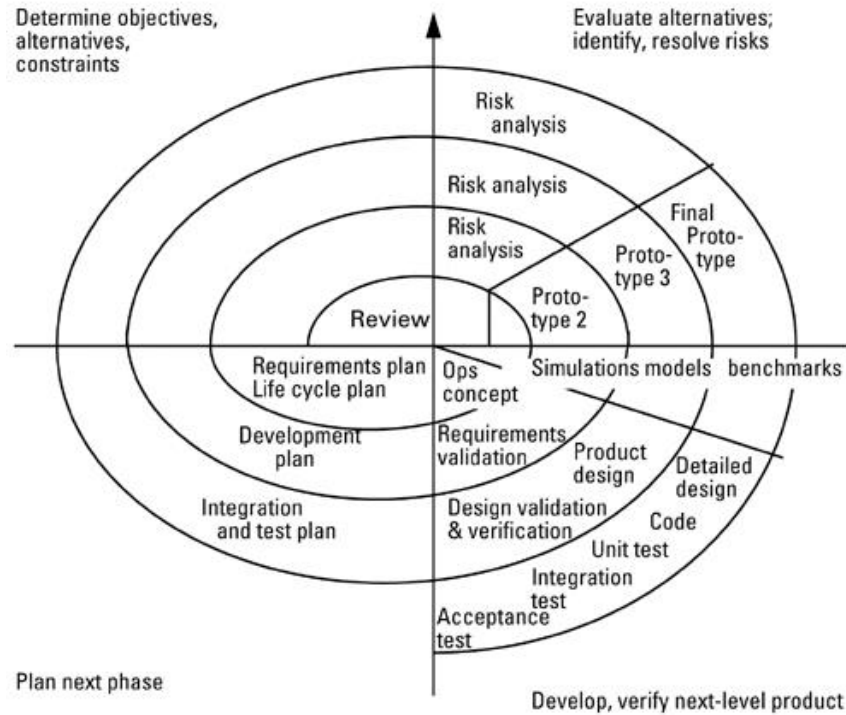


Figure 1. Spiral Process Model (Nielsen, 1993)

The risk assessment and reduction sector focuses on identifying risks and minimizing them. Reducing the risks may come from any number of methods to include altering the design, placing safeguards, or altering the method of production. The risks in question can range from imperfections in the product, imperfections in the manufacture of the product, or even safe use of the product. The spiral then moves to the next phase, development and validation, once all risks have been identified and mitigated as much as possible (Mohammed et al., 2010).

The development and validation sector generates the first prototype and begins the initial round of simulation and testing. This stage of the spiral is key, because the data and results further define the objectives and requirements of the final product.

Depending on the outcome of the initial round of testing and simulation, the design and objectives can change dramatically, which is discussed in the next sector, planning (Mohammed et al., 2010).

The planning sector takes all the information gained during the previous phase and, as the name suggests, plans for the next phase of the spiral. The producer reviews the simulation data, initial product tests and surveys, etc., to extract lessons learned and key takeaways to enhance the next phase. After this sector, the next spiral phase repeats the entire process until the final prototype is developed, at which point the design and the product are ready for full production (Mohammed et al., 2010).

The Spiral Method, as described above, was used in the research conducted by Shields (2016). During the course of his investigation, Shields (2016) employed the spiral method to develop multiple tools and jigs to include an EOD bracket to hold multiple sensors; a computer engineering microchip jig to aid AFIT students in the construction, repair, and modification of microchips by holding the main board completely still; a bracket for a utility pipe inspection autonomous vehicle to hold a front camera and light, detection, and radar (LIDAR) sensor; a rear LIDAR sensor for the same autonomous vehicle; and large and small battery receptacle for the utility pipe inspection vehicle. To conduct the development and validation portion of the spiral method, Shields (2016) developed a 19-question survey to test for usability. Those questions measured the five main characteristics of usability: learnability, efficiency, memorability, errors, and satisfaction (Nielsen, 1993).

The research conducted in this thesis used a similar set of questions with some additions. To preserve the baseline of core questions, some were reused, as this thesis is

a continuation of the work done by Shields (2016). The additions involved adding a question regarding how the topology optimization, if applied, affected the five characteristics listed above. Each user for the individual designs was given a set of randomized questions, with some being reverse-coded to ensure the person being surveyed thoroughly read and answered the questions truthfully. The set of survey questions utilized in the surveys as well as the Institutional Review Board package can be found in Appendix A.

### ***Explosive Testing for Munroe Effect***

Several designs were developed to create training versions of metal-shaped charge molds, explosive testing on these designs was conducted in conjunction with the usability test. These tests furthered the research conducted by Alwabel, Greiner, Murphy, Page, Veitenheimer, and Valencia (2017) in their research on 3D printed tools and training aids for EOD. The cuts made by the original versions, and the printed versions of the shaped charges, were compared by measuring the width, depth, and length on a steel plate, which is known as a “truthing” plate. These cuts are known as the “Munroe Effect,” which describe the mirroring cut made by the specific shape of the mold holding the explosive (Walters, 2007).

## **Materials and Equipment**

### ***Printer and Materials***

AFIT had several additive manufacturing machines available; however, this thesis only utilized one for consistency of material, print, and post-processing technique among

the different prints. The printer employed for this research effort was a 3D Systems ProJet 3500 HDMax, and post-processing was executed using the accompanying ProJet oven, set to approximately 70 degrees Celsius; both are shown in Figure 2. The primary printer used to conduct the research in this thesis comprised of a build space 11.75” x 7.3” x 8”. The materials used for each print include multiple colors of ABS plastic compatible with the printer and a wax support material.



Figure 2. Project 3500 HDMax printer and Post-Processing Oven

### *Software*

Multiple software packages were employed throughout the course of this research. A computer-aided design (CAD) software package, Autodesk Solidworks®, was used to generate the 3D renderings of the different designs and their iterations, as well as to create the .stl files for printing. Several software programs were investigated for the application of topology optimization; however, the program applied was

SolidThinking Inspire®. Additionally, Inspire® was also utilized to conduct finite element analysis on the same designs to ensure the strength of the optimized parts.

## **Procedures and Processes**

As stated in previous sections, the spiral method was used throughout the design process. Once a design possibility was chosen, an initial user interview was accomplished to determine overall product and user requirements. The initial prototype was developed incorporating initial design requirements set forth by the user. This process typically required two to three weeks per iteration. The prototype was then printed, post-processed, and provided to the user for initial testing and general feedback. This process was repeated, as defined by the spiral method, until the user accepted the final prototype. If possible, topology optimization was then performed on the final prototype—in an attempt to save material and overall product cost.

The various tools and jigs developed for this study stemmed from multiple agencies across the Air Force. The sources of these design requests included the 788<sup>th</sup> EOD Flight at Wright-Patterson Air Force Base, AFCEC, and several students conducting research in the AFIT Graduate School of Engineering Management Laboratory. Through these diverse end-users, nine unique products were developed: plastic version of the Mk 7 Linear-Shaped Charge, Conical Shaped Charge, Omnidirectional Shaped Charge Carrier System, Nonmetallic Probe, “Blue Devil” Detonation Cord (Det Cord) Connector, Respirator Bottle Holder, Cuvette Holder for spectrometer experiments, Gas Purifier Canister Supports, and Aerosol Nozzle for an unmanned aerial vehicle (UAV).

## **IV. Analysis and Results**

The previous chapter outlined the methods and tools utilized in this research effort. This chapter describes the various user design requirements, specifications, design iterations, and survey usability scores of the following designed tools and jigs: plastic version of the Mk 7 Linear-Shaped Charge, Conical Shaped Charge, Omnidirectional Shaped Charge Carrier System, Nonmetallic Probe, “Blue Devil” Detonation Cord (Det Cord) Connector, Respirator Bottle Holder, Cuvette holder for spectrometer experiments, Gas Purifier Canister Supports, and Aerosol Nozzle for an unmanned aerial vehicle (UAV). Additionally, this chapter also reviews the results of the User-Centered Design Survey focusing on multiple facets of usability, as described in the previous chapter.

### **Case Study 1: Mk 7 Linear-Shaped Charge**

The 788<sup>th</sup> EOD Flight at Wright-Patterson Air Force Base had several ideas for additively manufactured tools and jigs, the first being the Mk 7 Linear-Shaped Charge. Continuing the work accomplished by Alwabel et al. (2017), this research took the linear shaped charge they developed, Figure 3, and worked to improve it to meet the demands set forth by the 788<sup>th</sup>.



Figure 3. Original Mk 7 (left), Printed Mk 7 w/ 1 Copper Sheet (center), Printed Mk 7 w/ 2 Copper Sheets (right) (Alwabel et al., 2017)

### *Specifications, Requirements, and Design Iterations (Spirals)*

Similar to the design requirements listed in the research accomplished by Alwabel et al. (2017), the 788<sup>th</sup> EOD Flight asked for a printable version of the Mk 7 that had the same interior shape and volume as the original, metal Mk 7. Additionally, there were new requirements to make the printed Mk 7 as sturdy as possible, or “EOD-proof” as they stated, to make the printed Mk 7 level across the entire length, and to make it easy to line multiple printed Mk 7’s in a row.

Taking the design file from Alwabel et al. (2017), the first iteration corrected the internal geometry and volume errors. This was accomplished by taking precise measurements of the original and making an exact copy, apart from the legs which were designed to keep the jig level across its length and easier to align with other printed Mk 7s. The thickness was also kept the same as the original to explore the durability of the print medium. While the internal geometry and volume errors were corrected, the print, Figure 4, was much too fragile for the customer’s liking. As an example, four Mk 7s



were printed for this iteration; however, three broke during transportation to show the 788<sup>th</sup> EOD Flight.

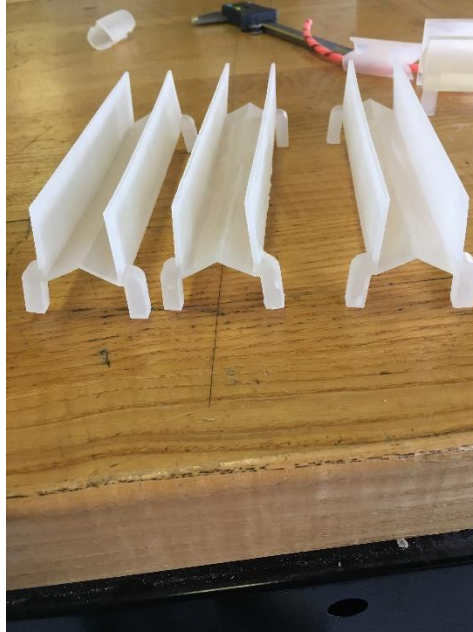


Figure 4. First Iteration Printed Mk 7

The goal of the next iteration was to improve the strength of the part, and mitigate the risk of breakage and injury to the user, by increasing the thickness of the print. The second iteration doubled the thickness of the original metal Mk 7. This iteration proved to meet the customer's need much better than the first because, as of the time of writing, none of the printed Mk 7 from this iteration, Figure 5, have been broken through either use or accident.



Figure 5. Second Iteration Printed Mk 7

### *Survey Results*

Table 3 shows the results of the survey. All questions for each aspect of usability were sorted before the descriptive statistics were run. There were several aspects of usability that had a wide range of answers across the various questions, but most scored rather high on the seven-point Likert Scale. The exceptions were quality, effectiveness, and utility. The respondent used the topology optimization comments section to explain why those in particular were lower. They remarked that the reason those areas were lower were based primarily on the print medium. Due to the type of operations EOD conducts, the plastic used is typically going to be too weak and brittle for expeditionary environments. However, they also mentioned that the part is a great way to overcome supply issues for training and expressed the versatility of AM in the future for their operations as the available print mediums increase and incorporate stronger materials.

Additionally, the utility scores are low due to the very specific purpose this jig was designed to accomplish.

Table 3. Printed Mk 7 Survey Results

<b>Mk 7 Linear Shaped Charge</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	7	5	1	3.055
<b>Effectiveness</b>	6	3	0	4.24
<b>Efficiency</b>	7	6	5	1
<b>Safety</b>	6	6	6	.*
<b>Utility</b>	7	4	1	3
<b>Learnability</b>	7	6	2	2.65
<b>Memorability</b>	6	6	6	0

\*There was only one response, so no standard deviation could be determined

### *Explosive Testing*

The printed Mk 7 was put head-to-head against the original, metal Mk 7 to further test the design's effectiveness, with the results shown in Figure 8. The weight of the original Mk 7 before adding the C-4 explosive was 5 oz, and the weight of the printed version was 2 oz. Personnel from the 788<sup>th</sup> EOD Flight placed 5.1 oz of C-4 into each container with a standard electric blasting cap to ensure identical conditions. Figure 6 shows the results of the testing on the steel truth plate. While the width of the cuts formed from each explosive jet varied greatly, the depth of the cuts only varied by 3 mm. The original Mk 7 Mod 8 linear shaped charge penetrated 14 mm, and the printed version penetrated 11 mm. The difference in cut width could be due to the material strength of

the different containers. The plastic would not offer as much resistance as the metal because of the material properties. Additional testing and modifications are recommended before use in contingency environments; however, the design will work well enough with minor modifications for training purposes.



Figure 6. Printed Mk 7 Results (Top) and Original Mk 7 Results (Bottom)

### Case Study 2: Conical Shaped Charge

The requirements for this case study were similar to those of the linear shaped charge. The 788<sup>th</sup> EOD Flight required a print that could withstand some abuse and

mimicked the interior geometry and volume of the original. Additionally, they requested that the printed conical shaped charge not have the long legs attached to the body similar to the original, but instead have extrusions with holes to accommodate 14-gauge wire. The 14-gauge wire would then be routed through the holes and act as the legs. The 788<sup>th</sup> EOD Flight requested this change for convenience and comfort during operations, as the legs of the original, shown in Figure 7, can poke them in the back when carried with their gear.



Figure 7. Original Conical Shaped Charge

This design effort required two design iterations. The first created the main body that mimicked the interior geometry and volume, and created extrusions with holes for 14-gauge wire, as requested. However, inexperience with the software led to a solid cone

being printed. When shown the first iteration, the 788<sup>th</sup> EOD Flight expressed concerns over whether or not the printed version would create the same cuts as the original due to the solid cone. It was theorized that the lack of at least some sort of empty space under the shaped charge would limit if not eliminate the formation of the jet that would cut the truth plate. Additionally, the holes for the 14-gauge wire were too small to fit the wire through.

The second iteration fixed both of those errors. The holes for the 14-gauge wire were expanded, and a cut was made into the bottom of the cone in the software to create a cone-shaped space under the shaped charge. The changes were met with great enthusiasm by the 788<sup>th</sup> EOD Flight. The second iteration print is shown in Figure 8.

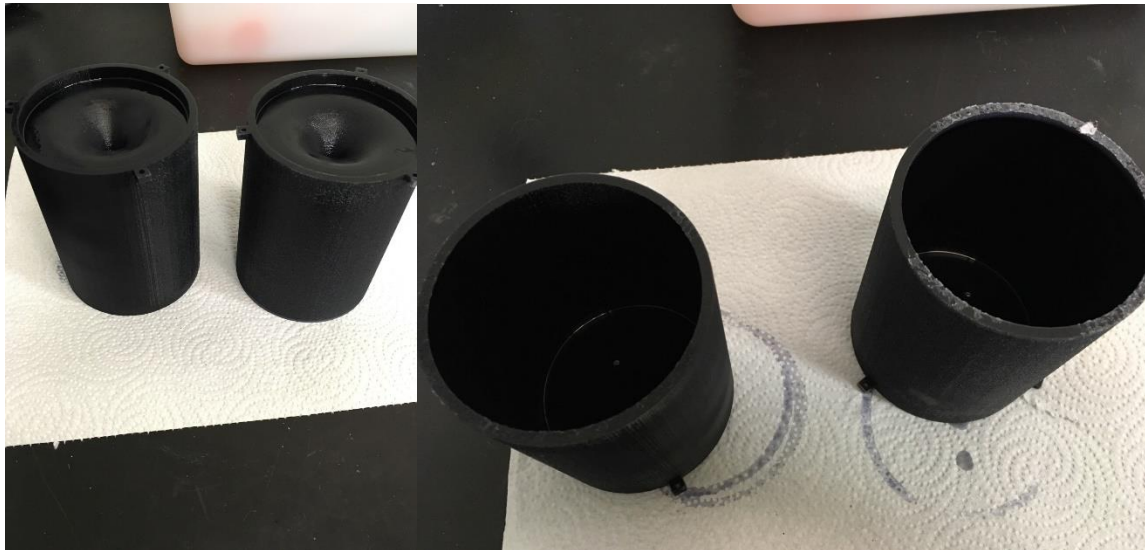


Figure 8. Second Iteration Conical Shaped Charge, Bottom View (left) and Top View (right)

### *Survey Results*

Unfortunately, no usability data were collected for the conical shaped charge. The people asked to complete the survey chose not to participate. There were no adverse reactions/actions taken against the respondents.

### *Explosive Testing*

Personnel from the 788<sup>th</sup> EOD Flight additionally tested the cutting capability of the conical shaped charge. However, the printed version failed to form a jet, thus no cut was made into the truth plate. While this test might have been a failure, further modifications and testing could result in a jet formation and mimic the cut of the original. Further modifications and testing are recommended.

### **Case Study 3: Omnidirectional Shaped Charge Carrier System**

The third case study explored was the omnidirectional shaped charge carrier system. The original requirement came from AFCEC; however, due to time and manpower turnover, feedback and additional requirements came from the 788<sup>th</sup> EOD Flight as they would be the end-users. The original requirements were for a carrier system capable of carrying six omnidirectional shaped charges. It was envisioned to be pulled by a robot and left behind for detonation. The first iteration consisted of a bottom to hold the shaped charges, sides with holes for wheels, and a top with holes to support the shaped charges with an additional hole for either a handle or chord to pull the carrier system, shown in Figure 9.



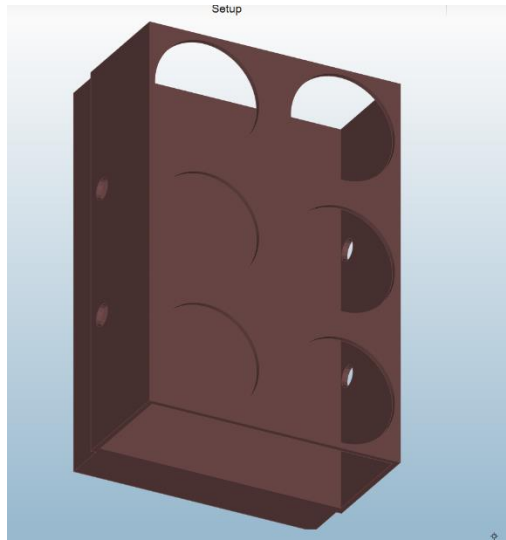


Figure 9. First Iteration Omnidirectional Shaped Charge Carrier System

The second iteration was based on feedback from the 788<sup>th</sup> EOD Flight. During an evaluative first look at the design, a discussion took place about the wheels. It was pointed out that as they were to be additively manufactured, they could prove to be a point of failure. If a wheel were to fail during operations, an EOD person would then have to don a bomb suit and go downrange into possible danger to replace it. Additionally, EOD currently employs sleds or sled-like objects to be pulled by robots for similar operations. Based on these discussions, it was decided to leave the holes for the wheels so the customer could use them if desired; however, a second hole would be added to the top so that a handle could be placed over the middle of the carrier system for the robot to carry or pull as desired or needed.

The last iteration involved topology optimization. As this could be used in expeditionary environments, the use of topology optimization to minimize the amount of material used proved to be ideal. The first attempt at topology optimization is shown in



Figure 10, which had no constraints on the design area (the area that could be reduced). The goal selected for all attempts were to reduce the amount of material by approximately 70%. The application of topology optimization will be discussed further in this chapter.

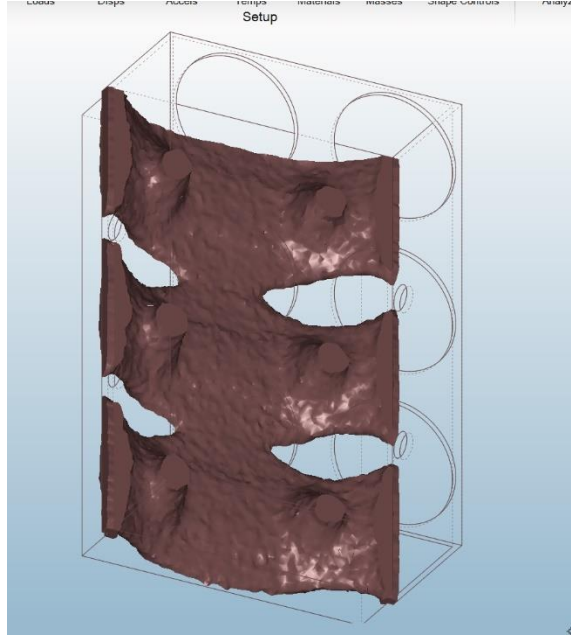


Figure 10. First Iteration Topology Optimization for Omnidirectional Shaped Charge Carrier System

The topology optimization software did indeed remove plenty of material; however, there was no way to keep the omnidirectional shaped charges in place during transit, shown in Figure 10. So refinements were needed to produce an optimal design that balanced the amount of material used and the design requirements. After several unsuccessful iterations, a balance was finally struck as shown in Figures 13 and 14. The loads applied for this design case include the weight of the bottles filled with water to the

bottom plate, the weight of the filled bottles and carrier to the handle holes, and the cumulative weight distributed among the support holes for the wheels. During the analysis, the goals for the topology optimization calculations were to remove up to 70% of the material (default setting) while maintaining the strength needed for the load case described earlier. Figure 11 is the result of this set of calculations, and Figure 12 shows the finite element analysis conducted by the software to prove that the design would be durable and meet the designed load case.

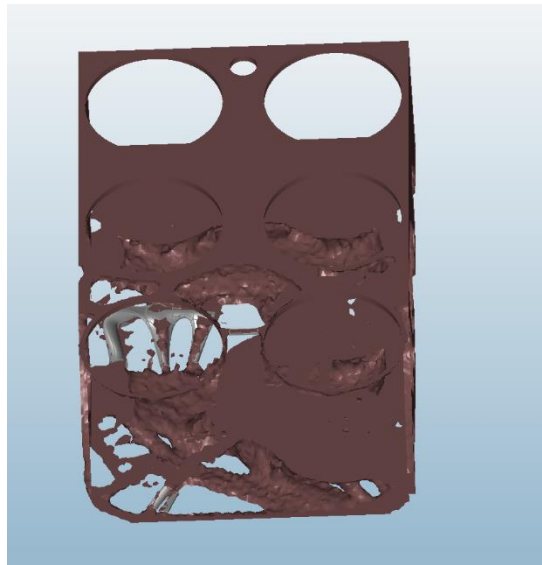


Figure 11. Optimized Omnidirectional Shaped Charge Carrier System

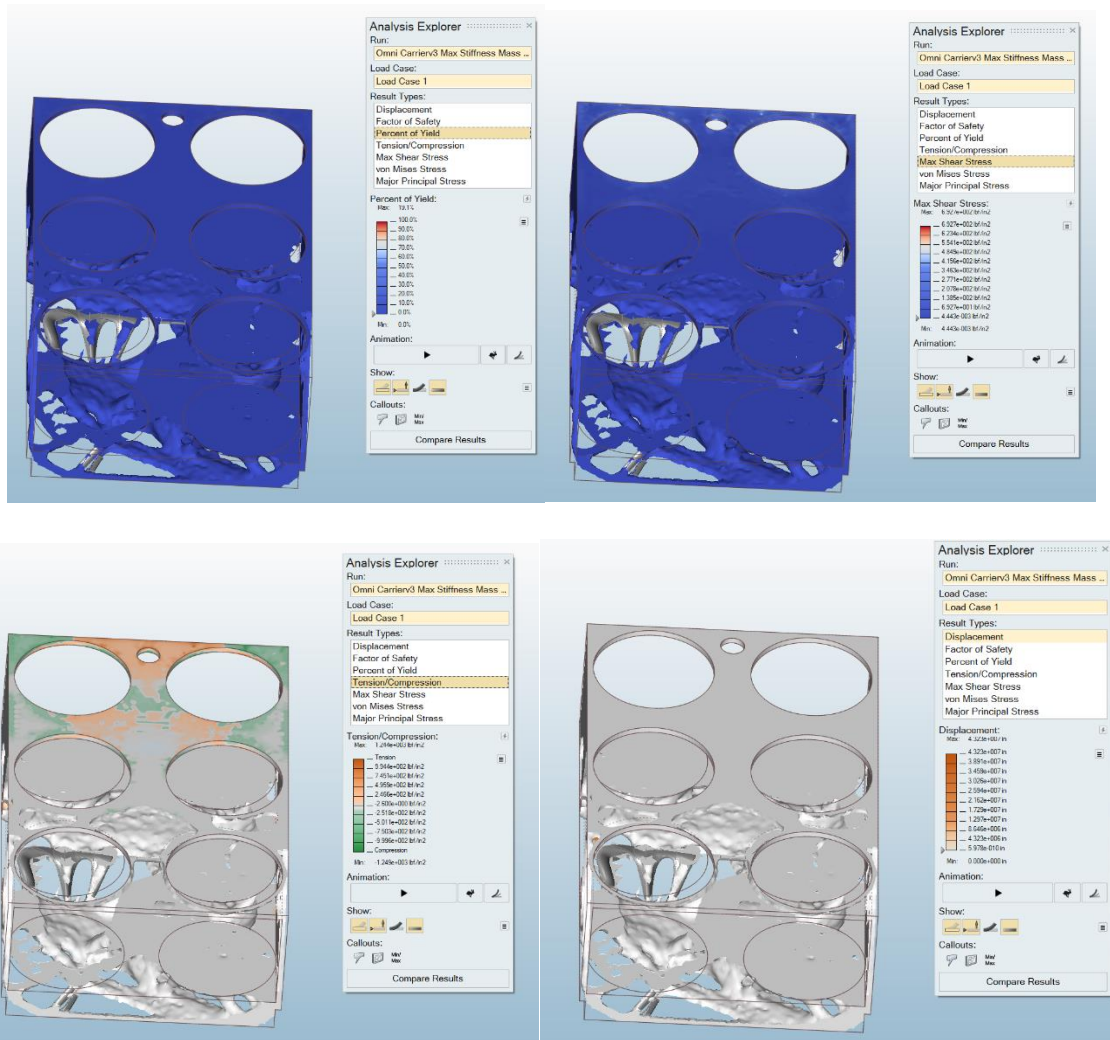


Figure 12. Percent of Yield (Top Left), Max Shear Stress (Top Right), Tension/Compression (Bottom Left), and Displacement (Bottom Right)

### Survey Results

Table 4 shows the results of the survey for this case study. This design exceeded all aspects of usability, according to the survey, except for efficiency which was left blank. Additionally, while topology optimization was applied to this design, no survey question was answered on this subject. Thus, no data or inferences can be made about the application of topology optimization for this part. What conclusions can be drawn

from the data, however, is that the carrier system met all specifications and requirements. It exceeded all metrics for usability by producing a design that consisted of great quality, was effectively designed, very safe to use, had great utility, and was easy to learn and memorize. On the other side of the coin, however, it could also mean that the respondent wanted to give a good review for the part and simply answered all the questions with a 7. Then the results would be meaningless given that scenario. More research should be conducted on this part to ensure that the part does meet all usability criteria, and to test whether the respondent gave an accurate depiction of the design during the survey.

Table 4. Omnidirectional Shaped Charge Carrier System Survey Results

<b>Omnidirectional Shaped Charge Carrier System</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	7	7	7	0
<b>Effectiveness*</b>	7	7	7	-
<b>Efficiency**</b>	-	-	-	-
<b>Safety*</b>	7	7	7	-
<b>Utility*</b>	7	7	7	-
<b>Learnability</b>	7	7	7	0
<b>Memorability*</b>	7	7	7	-

\*Only one question was answered in this section, thus no standard deviation could be calculated

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#### Case Study 4: Nonmetallic Probe

The fourth case study focused on a nonmetallic probe. The design requirements were to create a sturdy probe that could puncture through different soil conditions, minimize the amount of soil disturbed, be comfortable to use, be nonmetallic to prevent static discharge, and potentially have 1" marks to help gauge the size of objects in the field. The 788<sup>th</sup> EOD provided two different examples of nonmetallic probes currently employed as shown in Figure 13.



Figure 13. Examples of currently employed Nonmetallic Probes

For the first design iteration, the example on the left in Figure 13 was used as a model and included  $\frac{1}{2}$ " and 1" incremental marks along the length of the blade. However, the printed version, Figure 14, was too thin and brittle to be used in anything but loose sand. Even then, it could prove to be a risk to the person using it. For example, the author was able to break the printed first iteration between two fingers and ended up cutting a finger on the broken plastic.

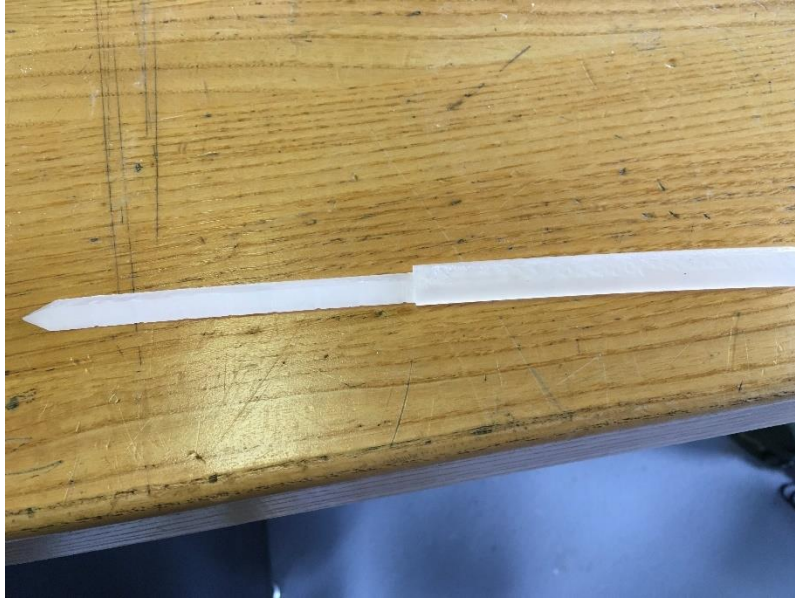


Figure 14. First Iteration Nonmetallic Probe

The second iteration, Figure 15, corrected this by adding more material and using the nonmetallic probe on the right of Figure 13 as a model. This added strength to the print; however, the incremental marks were mistakenly cut too deep into the blade, thus causing it to snap when attempting to probe compacted soil outside the 788<sup>th</sup> EOD Flight building. Additionally, the length of the handle was approximately 2” too long, by estimation of the customers.



Figure 15. Second Iteration Nonmetallic Probe

The third and fourth iterations, Figure 16, were inspired by a homemade probe developed by one of the EOD technicians. They had made a very long and thin probe made of fiberglass, which was very sturdy and barely disturbed the soil. The third iteration was a direct copy of the homemade probe, while the fourth iteration resulted in a modular version. A hollow tip with hollow attachable segments were created so that an EOD technician could fill the tip with fiberglass or epoxy, add a new segment and fill that with the same material, and continue until they had a probe of suitable length. The shape of this probe would ensure minimal soil was disturbed, while the addition of an added medium in the middle would increase the overall strength of the part.



Figure 16. Fourth Iteration Nonmetallic Probe

While the third and fourth iterations were an interesting path to follow, the majority of the EOD flight preferred the size and shape of the second iteration, so a fifth iteration fixed the issues of the second. The handle was shortened by 2”, the depth of the incremental marks was decreased, and a fillet was added to create a smoother transition between the blade and handle to minimize stresses in that area.

### *Survey Results*

Table 5 shows the survey results for this case study. Two of the three respondents rated the probe very highly across the board. Interestingly, the youngest respondent rated the probe significantly lower in quality, effectiveness, efficiency, and utility. Utility had an average median score and a high standard deviation. One inference from this data is that more possibilities for this tool become more apparent with additional training and experience. The median score for quality could be due to the overall flexural strength of the print medium. When tested in compacted soil, or even in colder weather, the probe broke relatively easily. The respondents, and other SMEs in the 788<sup>th</sup> EOD Flight expressed hope for stronger print mediums to be able to utilize the designed probe more effectively and with greater results. Effectiveness showed a wide range of scores, and a large standard deviation, but the median score showed that the probe was effective in its job. Safety, learnability and memorability also had low standard deviations and high median scores.

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Table 5. Nonmetallic Probe Survey Results

<b>Nonmetallic Probe</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	7	5	2	1.45
<b>Effectiveness</b>	7	6	3	1.56
<b>Efficiency</b>	7	6	0	2.24
<b>Safety</b>	7	7	6	0.58
<b>Utility</b>	7	5	2	2.19
<b>Learnability</b>	7	7	5	0.71
<b>Memorability</b>	7	7	6	0.41

#### **Case Study Five: “Blue Devil” Detonation Cord Connector**

The “Blue Devil” detonation cord (det cord) connector is the fifth case study that will be explored. The 788<sup>th</sup> EOD Flight requested this be designed due to the possible applications and the relative scarcity of a regularly manufactured Blue Devil. EOD technicians provided a picture of an original found on Google Images and some approximate dimensions. The overall design requirements were to design a Blue Devil to match the original and be of sturdy enough construction to be utilized in the field. The first iteration was based on the picture shown and the approximate dimensions given. However, the first iterations was much larger than the original. It was then decided to scale down the second iteration, and slowly increase the size until an exact size is matched. The next three iterations were too small and broke when attempting to connect two pieces of det cord. The fifth iteration finally met all specifications, to include

matching the exact size of the original and strength, by increasing the print thickness.

Figure 17 shows the first and fifth iterations of this case study.



Figure 17. First (left) and Fifth (right) Iteration Blue Devil

### *Survey Results*

Table 6 shows the survey results of this case study. Overall, the blue devil scored well, except for quality, safety, learnability, and memorability. These areas of usability had lower median scores and high standard deviations. Safety, however, only had one response and no standard deviation could be calculated. The quality and safety scores are more than likely due to the brittleness of the material. This could possibly be improved by increasing the wall thickness. The scores for learnability and memorability are a bit of a conundrum. They could be due to the large amount of training that is required before one can be utilized and the scarcity of the original. The median scores show that the tool is of median quality, is effective and efficient in its use, moderately safe to use, has great

utility, and is moderately easy to learn and memorize for operational use. All areas except for effectiveness had high standard deviations.

Table 6. Blue Devil Survey Results

<b>Blue Devil</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	6	4	3	1.53
<b>Effectiveness</b>	6	6	6	0
<b>Efficiency</b>	6	6	3	1.73
<b>Safety*</b>	4	4	4	-
<b>Utility</b>	6	6	1	2.89
<b>Learnability</b>	7	5	0	3.61
<b>Memorability</b>	7	5.5	4	2.12

\*Only one response, no standard deviation could be calculated

### **Case Study Six: Respirator Bottle Holder**

The next case studies were specifically for Masters and PhD students utilizing the Air Force Institute of Technology Graduate of Engineering Management Laboratory. This case study was to create a support for up to nine glass bottles. There was only one design iteration due to minimal additional feedback from the customer. The design requirements were for an elevated support structure to keep up to nine glass bottles in place during experiments. Given the size of the bottles, the experiment area, and the size of the print space, it was decided to print the support in three parts. To increase stability

as well as add a scalable component, holes and pegs were added to each of the three sections. The first section had the capacity to hold two bottles, the second section three, and the third section four. This allowed for the experiments to be scalable from two bottles all the way up to nine. Figure 18 shows the holder in use during an experiment.

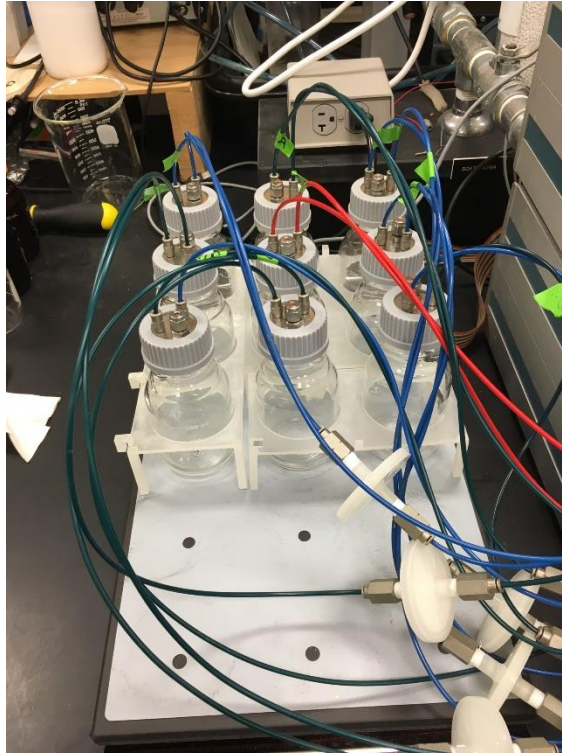


Figure 18. Respirator Bottle Holder

### *Survey Results*

Overall, the holder scored extremely well except in effectiveness and utility. Remarks made in the section for topology optimization comments state that the effectiveness score was lower because the weight of the bottles caused the middle of the

sections to bow. This could be fixed by increasing the thickness of the sections and adding additional legs to support the weight. The utility score is due to the limited amount of additional uses this jig has because it was designed for a very specific task. The highest standard deviation was quality. Everything else either had an extremely low standard deviation, or it could not be calculated due to only one question being answered in that particular section. Table 7 shows the results of the survey.

Table 7. Respirator Bottle Holder Survey Results

<b>Respirator Bottle Holder</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	6	6	2	2.31
<b>Effectiveness</b>	6	4.5	4	0.96
<b>Efficiency</b>	7	7	7	0
<b>Safety*</b>	7	7	7	-
<b>Utility*</b>	4	4	4	-
<b>Learnability</b>	7	7	7	0
<b>Memorability</b>	7	7	7	0

\*Only one question was answered, no standard deviation could be calculated

### **Case Study 7: Cuvette holder for spectrometer experiments**

For the seventh case study, the Laboratory requested a replacement for a metal cuvette holder used in their spectrometer. The original requirements were to mimic the exact size and shape of the metal holder and to print the holder using black plastic. The

first iteration was an exact replica of the original and performed during the experiments just as well as the original. Once the first iteration and round of experiments were completed, the Laboratory asked for additional holes along the length of the base to accommodate screws to alter the height and angle of the holder to ensure a clear line of sight for the laser in the spectrometer. The second iteration added these holes.

Once the second iteration and round of experiments were completed, one last change was requested. The Laboratory asked for a reduced opening along the shaft of the holder to decrease the amount of light reflected away from the sensor behind the cuvette holder. The third iteration, Figure 19, fulfilled that requirement. A fourth iteration applied topology optimization to the base of the holder, and it took away all of the space between the screw holes. Lengths of materials were added to create bridges between the holes, but the customer did not want to print this design due to the remote possibility of the holder breaking during experiments.

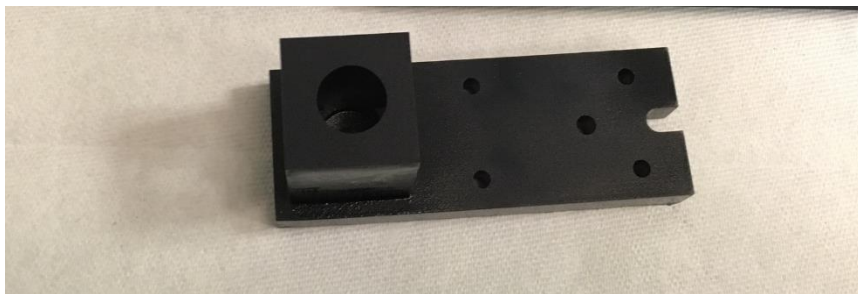


Figure 19. Third Iteration Cuvette Holder

The customer asked approximately how much each print cost to compare to their invoice for a new cuvette holder. Based on the cost of one bottle of plastic and one bottle of the wax support material, it was extrapolated that each printed cuvette holder was approximately \$40. Compared to the invoice of the original, unaltered metal cuvette holder, there was a significant savings. Over the course of the three prints, it was determined that utilizing AM saved the Laboratory approximately \$3,000.

### *Survey Results*

Table 8 shows the results of this survey. The design scored well across the board, with the exception of utility. The lower score is sensible because it was designed for a very specific task. Topology optimization scored well considering it was not printed. The respondents did not leave any comments regarding the addition of topology optimization to the design. Overall, the median scores suggest the jig was a quality design that is effective, efficient, safe to use, and easy to learn and memorize. Additionally, the median score for topology optimization shows that its application added some value to the overall design and could increase cost savings.

**\*\*This section was left blank**

Table 8. Cuvette Holder Survey Results

<b>Cuvette Holder</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	7	7	7	0
<b>Effectiveness</b>	7	7	1	2.55
<b>Efficiency</b>	7	7	7	0
<b>Safety</b>	7	7	7	0
<b>Utility</b>	7	3	0	1.34
<b>Learnability</b>	7	7	0	3.03
<b>Memorability</b>	7	7	7	0
<b>Topology Optimization</b>	7	5.5	4	2.12

### Case Study 8: Gas Purifier Canister Supports

This case study came from a PhD student utilizing the laboratory. The design requirements were to create a support system to hold a gas purifier canister vertically against a table leg. Additionally, the top piece should have holes to increase the air flow if the student decided to remove the canister cap. The first iteration included a rounded base and top with vertical walls to help hold the canister upright; it also included parallel extrusions with holes on the far side of the table leg for nuts and bolts to help keep the whole system from being jarred or otherwise moved. However, the extrusions in the first iteration were canted at an angle, thus keeping the top from being able to meet the rest of the canister. The second iteration corrected this error, Figure 20. The nuts and bolts required approximately five iterations to get the size and space tolerances correct.



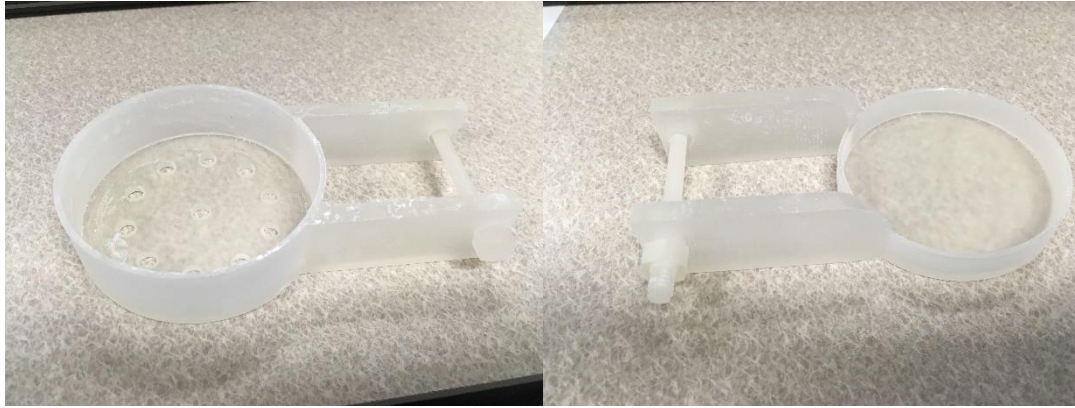


Figure 20. Second Iteration Gas Purifier Canister Supports w/ Nuts & Bolts

### *Survey Results*

Table 9 shows the results of the usability survey. The scores for usability were fairly consistent with this design. The overall scores were high, with the exceptions of quality and utility. The median quality score could be lower due to the strength of the print medium in conjunction with the relative thinness of most of the dimensions. If the gas purifier were to be knocked relatively hard, the entire support structure could fracture, potentially ruining the running experiment. The utility score was also low, which was foreseen because this design is very specific to one purpose. Given the lab setting, there is not much else this design could be used for. The rest of the scores point to a well-designed jig that is effective, efficiently designed, safe, and easy to learn and memorize. Additionally, the high score for topology optimization signifies that the use of it added value to the overall design.

Table 9. Gas Purifier Vertical Support Survey Results

<b>Gas Purifier Vertical Supports</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	6	4	3	1.53
<b>Effectiveness</b>	7	7	7	0
<b>Efficiency</b>	7	7	7	0
<b>Safety*</b>	7	7	7	-
<b>Utility</b>	2	1	0	1.41
<b>Learnability</b>	7	6	1	3.21
<b>Memorability</b>	7	6	5	1.41
<b>Topology Optimization*</b>	7	7	7	-

\*Only one question answered, no standard deviation could be calculated

### Case Study 9: UAV Aerosol Nozzle

For this case study, the requirements were to mimic an existing aerosol nozzle to help a Master's student in their research. The student was unable to procure the existing nozzle due to limited time and funds. The first iteration mimicked the original exactly, but tolerances between several of the pieces were too tight and the screws meant to hold everything together were too small and brittle. A second iteration fused several parts together and corrected the tolerance error, Figure 21. According to the customer, the second iteration works just as well as the original.

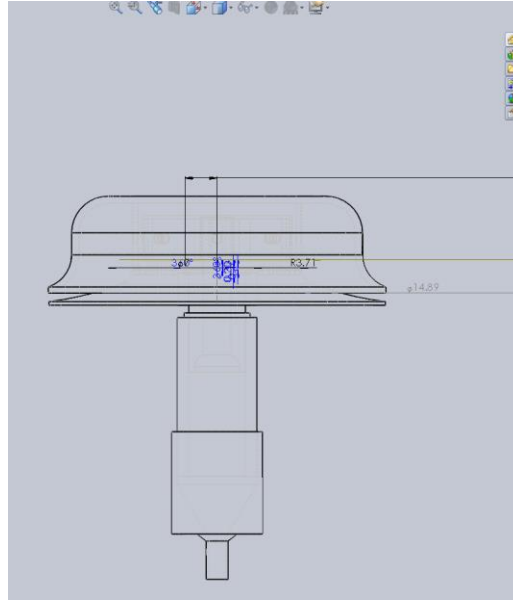


Figure 21. Second Iteration Nozzle Assembly

### *Survey Results*

Table 10 shows the results of this survey. Overall, this design had widely ranging scores. The median scores across all areas of usability point to an average tool design. However, comments from both participants in the section meant for topology optimization mentioned that the printed aerosol nozzle performed just as well as the original manufactured part. While the scores reflect an average design, this points more to the manufactured part as this design effort replicated the original with only modest modifications. The fact that the printed part works just as well as the original reflects the versatility and utility of AM. More research can be accomplished to see what other applications are available for more cost effective part replacement.

Table 10. UAV Aerosol Nozzle Survey Results

<b>UAV Aerosol Nozzle</b>				
	<b>Maximum</b>	<b>Median</b>	<b>Minimum</b>	<b>Standard Deviation</b>
<b>Quality</b>	6	4	3	1.37
<b>Effectiveness</b>	6	5	2	1.41
<b>Efficiency</b>	7	5	2	1.86
<b>Safety</b>	7	6.5	6	1.86
<b>Utility</b>	6	4	1	1.97
<b>Learnability</b>	5	3	2	1.03
<b>Memorability</b>	7	5	3	1.63

### Case Study Trends and Analysis

By analyzing the descriptive statistics between the nine case studies, several trends can be identified between the various aspects of usability. Quality scored high for the most part, but there were a couple cases that scored average values. In these cases, the respondents commented on the strength of the material as the reason why. Those designs could have potentially been improved through either additive materials to the print, such as carbon fiber or Kevlar fibers implanted into the print through the use of a different printer, or by using a stronger material.

The median values for effectiveness were high, with three exceptions. The linear shaped charge scored a three, possibly due to the measured cuts from the Munroe Effect testing. The penetrations were only 3mm off, but the widths of the cut were significantly different. The respirator bottle holder scored a median value of 4.5 due to deflection of the holder once all the bottles were in place. The third case with a lower median value

was the UAV Aerosol Nozzle. The median value was a 5, so the score was average. This seems counterintuitive, however, based on the comments that the printed version performed just as well as the original. It could be due to the brittleness of the print medium making the part more likely to break during operations than using the original metal. If this is the case, then all three median scores that were below a 7 were due to the material properties of the print medium. For all other cases, however, the designs scored extremely high for effectiveness.

The median scores for efficiency were all 5 or above, with only one case scoring at a 5, and two cases at a 6. The cases that scored below a 7 had a standard deviation between 1 and 2.24, suggesting that at least one respondent scored the case at a 7. The lowest efficiency median score was for the UAV Aerosol Nozzle. As stated in the previous paragraph, this seems counterintuitive based on the comments that the printed performed just as well as the original. All other cases scored a perfect 7 with a standard deviation of 0, with one case not receiving any feedback.

The next set of median values to be explored are for safety. Many of the cases scored between 6 and 7, with only one case being scored at a 4. This particular case was the Blue Devil. There was only one question in the survey for safety, and only one person responded to the survey, so a standard deviation could not be calculated. The lower value could be due to the potential for breakage during use. If this is true, then the design could be improved by further increasing the thickness of the walls. The other designs were thought to be very safe to use, however.

Utility median scores ranged widely from a 1 all the way to a 7. The cases in which the scores were low all had a design that was suited to a very specific purpose. For

example, the lowest median score was for the Gas Purifier Vertical Supports. The laboratory environment for which this case was applied had a very specific purpose. The nature of each specific purpose lends itself to a low utility as the prints in those cases were only really suited for that one specific application. All of the cases in which the AFIT Graduate of Engineering Management Laboratory was the customer had a low utility score, whereas the cases in which EOD was the customer had larger utility median scores. This could be due to the nature of each customer, because the Laboratory has specific experiments while EOD has many environments and missions to which they must adapt.

Learnability median scores were between 6 and 7, with the exceptions of the UAV Aerosol Nozzle which scored a 3 and the Blue Devil which scored a 5. Since these prints were easy to learn, the respondents could have been looking at the prior training and education needed to use the parts effectively. For instance, the Aerosol Nozzle was easy to assemble; however, a fairly large amount of education is needed to analyze the effects and dispersion patterns of the nozzle. Similarly, the Blue Devil was very easy to use, but the training required to be able to use it safely in EOD operations is quite arduous and extensive. All other cases showed that the designs were easy to learn how to use correctly.

Memorability median scores ranged between 5 and 7. The standard deviations ranged from 0 to 2.12, with the larger standard deviations coming from the lower scoring cases. This means that at least one respondent scoring the case at a 7. Overall, even with the lowest score being a five, all cases showed that every case and design was easy to memorize its use.

## **Topology Optimization**

Topology optimization was applied to only a few select cases; Table 11 shows a summary of all the case studies, whether topology optimization was applied, and the reason. The criteria for the application of topology optimization to the individual case studies took place in the final spiral of design. If the customer and author found that topology optimization could improve the design by removing excess material for any reason, then an investigative design was accomplished. If the result met customer requirements and they were satisfied with the design, then the part was deemed final. If the customer did not approve the modifications that came with topology optimization, then the design was reverted to the last customer approved version. In total, three of the nine case studies applied topology optimization successfully.

When topology optimization was applied, the designs in each case study reduced material usage. For the omnidirectional shaped charge, a majority of the base, sides, and top of the design were removed, which resulted in approximately 70% of the material being removed. With the Cuvette Holder, approximately 70% of the material was also removed. In fact, bridges between the separate holes had to be placed in order for it to be one continuous part. The vertical support stands showed mixed results. The bottom stand only removed approximately 30% of the material, and only in the extrusions leading to the nut and bolt. The top stand removed approximately 70% of the material by removing the top section and a good amount of the extrusions leading to the nut and bolt. A bridge had to be created across the top to ensure that the top piece stayed on the gas purifier. Overall, the software met its goal of removing 70% of the material in almost every case study in which it was applied.

Table 11. Topology Optimization Summary

Topology Optimization		
Case Study	Applied?	Why
Linear Shaped Charge	No	More material was need to resist the explosive force of the C-4 to minimize excessing forces acting on the truth plate
Conical Shaped Charge	No	More material was need to resist the explosive force of the C-4 to minimize excessing forces acting on the truth plate
Omnidirectional Shaped Charge Carrier System	Yes	Large amounts of material in the design, in addition to the effect of logistics in a contingency environment, made this a perfect case for topology optimization
Nonmetallic Probe	No	Both the blade and the handle required smooth surfaces w/o pits or grooves in order to disturb the least amount of soil
Blue Devil	No	The design in this case was small and required all of the material in the design to meet operational specifications
Respirator Bottle Holder	No	The design was already minimal in its application, and deflection was already an issue. Topology optimization would not have made any significant improvement
Cuvette Holder	Yes	The size of the base section and the potential forces applied led to the believe that topology optimization could minimize the material in the base while preserving the strength of the holder
Gas Purifier Vertical Supports	Yes	The amount of material used in the base section of the holder led to an investigation on whether topology optimization could improve the design by minimizing the material while preserving the strength of the holder and without compromising the results of the experiment
UAV Aerosol Nozzle	No	This was an effort to replicate an existing product in order to save time and money. Additionally, topology optimization was not applied due to the very specific nature of the design to minimize flow of air into specific pathways in the nozzle. Additional holes or pits in the material could have adversely effected the performance of the nozzle



## **V. Conclusions and Recommendations**

This chapter draws conclusions from the data gathered through the Spiral Method and the Customer-Centered Usability Survey. Additionally, the significance of the research that was conducted and the answers to the original research questions are discussed. Lastly, recommendations for actions and future research are explored.

### **Conclusions of Research**

As stated in the previous chapter, most of the design efforts scored very well on the Customer-Centered Usability Survey. The ones that did not score very well were either designed for very specific uses, did not receive much customer feedback, or the material/shape was not adequate for the operational demands. Overall, however, value was added by pursuing these designs.

Based on the results from the 788<sup>th</sup> EOD Flight and the AFIT Laboratory, AM added value and flexibility to both operations. Unique tools and jigs were created, and logistical issues were overcome by the employment of AM. Based on these examples, AM can be employed in other career fields and operations across the Air Force, especially as the technology matures and more materials become available for prints.

The first research question asked to what degree can AM and topology optimization be utilized by the various Air Force squadrons in their day-to-day and contingency operations, based on the current state of technology? By applying AM and topology optimization to designs in EOD and a laboratory, this research effort shows that AM and topology optimization can be applied to a wide-range of day-to-day operations.

Both environments have specific needs and are very diverse in their function and operations. The application of these technologies shows how many different end-users can benefit from AM and topology optimization. However, questions arose from the SMEs about the quality of the print medium for use in contingency operations, which were reflected in the survey results. Given the current state of technology, use in both day-to-day and contingency operations is limited due to the strength of the print medium. The SMEs did, however, express great interest and excitement in the use of AM in contingency operations once stronger materials are made available for use in 3D printing.

The second research question asked to what degree can topology optimization be included into the tools and jigs developed for Air Force Operations? Through this research effort, only three designs were deemed appropriate for the inclusion of topology optimization. This may seem to be low, approximately 30% of the designs in this research, but that could be due to the nature of the designs chosen. A majority of the designs required either a smooth surface for holding/penetrating soil (nonmetallic probe), or designed to replace/supplement existing manufactured parts (linear shaped charge, conical shaped charge, cuvette holder, aerosol nozzle, blue devil). As such, topology optimization did not make too much sense. The vast majority of case studies intended for training and/or operational environments did not facilitate the application of topology optimization. This could indicate that in its current state, AM and topology optimization in contingency environments is limited. Further testing should be conducted to evaluate AM and topology optimization in contingency and humanitarian environments. However, there could potentially be many applications for topology optimization in other day-to-day operations. Aircraft repair, construction, and other areas

in the Air Force are ripe with possibilities for the application of AM and topology optimization. However, many parts for aircraft and construction are regulated by design specifications and regulations that are overseen by larger organizations such as the National Electric Code and the National Fire Protection Agency. Further research is recommended on how well AM parts and technologies can be applied to these codes and regulations, and if these technologies can be written into those same codes and regulations.

The third research question asked how much could topology optimization potentially save the Air Force over a given amount of time? This can be extrapolated given the application rate from this research effort, approximately 70%, and some basic assumptions. The default goal of the software package, Inspire, is to reduce the material used by 70%. If the conservative estimation of a material usage reduction of 40% per print, then an extrapolation of a 40% savings per bottle can be assumed. Given that one bottle of plastic costs approximately \$640 and one bottle of wax support material costs approximately \$400, then by using 40% savings, the USAF saves \$256 per plastic bottle and \$160 per wax support bottle. This savings will not show immediately in the bill, however, but will show by allowing more prints to be accomplished per bottle. On a larger scale, if the Air Force were to purchase 4000 bottles of plastic and 4000 wax support bottles in one year, the savings reached by applying topology optimization could reach up to \$1,024,000 for the plastic and \$640,000 for the wax support by delaying when the next batch of materials are needed.

## **Limitations of Research**

The research conducted during this thesis was limited in several ways. As there were multiple students studying AM, the amount of material used throughout the course of everyone's research had to be limited. In conjunction with the previous thought, communication for ordering new materials created obstacles. There was a point in time in which the amount of wax support material was running low, and there was a question on whether the Laboratory would purchase more. Because of the lack of communication on whether it would be ordered or not, as well as the limit on the number of wax bottles that were authorized to be stored, no additional bottles were ordered. This led to one design not being printed for the customer.

Other limitations include only one type of plastic for use in the printer. While multiple colors existed and were available in the lab, they all had the same properties. The largest limitation for this research was communication with the larger AF. When asked for design ideas for this research, the only entities to respond back were local units and AFCEC, which was already interested due to prior research. Had more units responded with ideas, this research could much better encapsulate the idea that many career fields can utilize AM.

## **Significance of Research**

This research shows that AM can be employed by various entities across the AF by applying these technologies to two diverse career fields and environments. The work accomplished for the 788<sup>th</sup> EOD Flight shows that AM can even find a home and add value to career fields that require very sturdy equipment, or equipment that could be

logistically challenging due to a number of factors. Other, similar career fields, such as Combat Controllers, Pararescuemen, Joint Terminal Attack Controllers (JTACS), etc., can potentially find uses for AM to solve many different problems. Civil engineers could use AM for noncritical parts, and possibly employ AM with concrete in expeditionary environments to create structures that are more small-arms fire resistant than tents with fewer boots on the ground. Additionally, those same techniques could create buildings that match the topography of the area and make buildings and bases much harder to spot using aerial surveillance. As the technology develops, the applications for AM become limited only by the imagination.

### **Recommendations for Action**

AM should be examined by operational career fields across the USAF, and even across the DoD, to see if there is any added value by the employment of 3D printers. More research should be funded by the USAF and DoD to increase the capabilities of AM, to include faster prints, stronger materials, and the use of concrete printing techniques suitable for expeditionary environments. Lastly, topology optimization should be reviewed as part of the overall design process to create new parts with unique geometries, encourage the use of fewer resources, and promote responsible engineering.

### **Recommendations for Future Research**

Future research ideas include a more in-depth look at the advantages and possible cost savings of topology optimization. Other recommendations include the properties of other materials in use for USAF operations, the development of specifications for the use of AM in construction, and the use of concrete printing in USAF Civil Engineering

operations. Additionally, the use of AM in contingency and expeditionary operations is great recommendation for future research.

## Appendix A – Institutional Review Board Exemption Package

DEPARTMENT OF THE AIR FORCE  
AIR FORCE INSTITUTE OF TECHNOLOGY  
WRIGHT-PATTERSON AIR FORCE BASE OHIO

24 January 2017

MEMORANDUM FOR LT COL MATTHEW DOUGLAS, PHD

FROM: William A. Cunningham, Ph.D.  
AFIT IRB Research Reviewer  
2950 Hobson Way  
Wright-Patterson AFB, OH 45433-7765

SUBJECT: Approval for exemption request from human experimentation requirements (32 CFR 219, DoDD 3216.2 and AFI 40-402) for your study An Analysis of the Practicality of Additive Manufacturing and Topology Optimization within United States Air Force Operations.

1. Your request was based on the Code of Federal Regulations, title 32, part 219, section 101, paragraph (b) (2) Research activities that involve the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior unless: (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) Any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.
2. Your study qualifies for this exemption because you are not collecting sensitive data, which could reasonably damage the subjects' financial standing, employability, or reputation. Further, the demographic data you are utilizing and the way that you plan to report it cannot realistically be expected to map a given response to a specific subject.
3. This determination pertains only to the Federal, Department of Defense, and Air Force regulations that govern the use of human subjects in research. Further, if a subject's future response reasonably places them at risk of criminal or civil liability or is damaging to their financial standing, employability, or reputation, you are required to file an adverse event report with this office immediately.

WILLIAM A CUNNINGHAM, PH.D.  
AFIT Exempt Determination Official

**Figure A-1. IRB Exemption Letter Dated 24 January 2017**

**DEPARTMENT OF THE AIR FORCE  
AIR UNIVERSITY (AETC)**

09 January 2017

MEMORANDUM FOR AFIT EXEMPT DETERMINATION OFFICIAL

FROM: AFIT/ENV  
2950 Hobson Way  
Wright Patterson AFB OH 45433-7765

SUBJECT: Request for exemption from human experimentation requirements (32 CFR 219, DoDD 3216.2 and AFI 40-402) for An Analysis of the Practicality of Additive Manufacturing and Topology Optimization within United States Air Force Operations.

1. The purpose of this study is to determine the potential value of Additive Manufacturing, or 3D Printing, capability within Air Force Squadrons. The objective of this research is to find solutions to 10 unique problems from various Air Force units using the Spiral Method of design, the use of a 3D printer, and the application of topology optimization. The results will provide validity to incorporate Additive Manufacturing into various units and squadrons across the Air Force to solve diverse problems.

2. This request is based on the Code of Federal Regulations, title 32, part 219, section 101, paragraph (b) (2) Research activities that involve the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior unless: (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) Any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

3. The following information is provided to show cause for such an exemption:

- a) Equipment and facilities: Survey will be conducted following the design, print, and testing of the additively manufactured tool or jig. It will be administered in person following the final test of the tool or jig. The survey will be in paper form to be printed with AFIT supplied paper and ink.
- b) Subjects:
  - Source of subjects – Subjects will be military and civilian personnel assigned to AFIT and the 788<sup>th</sup> Explosive Ordnance Disposal Flight between the grades of E-3 to E-7 and O-2 to O-4.
  - Total number of subjects: No more than 12 subjects will be given the survey.
  - Inclusion/exclusion criteria: 2 personnel per tool/jig who work with and understand the operation and use of the tool/jig.

**Figure A-2. IRB Memorandum for Exemption**



- Age range: Subjects will be 18 years of age and older.
  - c) Timeframe: The survey will be administered during the month of January 2017. The printing and testing of the tools and jigs is already underway and will be completed prior to the survey being administered.
  - d) Data collected: The survey will be anonymous and will not collect Personally Identifiable Information (PII). Demographics information collected will be limited to total number of years of service and job title. Survey format and questions can be seen in attachment 1. The principal investigator will securely store paper copies and digital analysis files of completed surveys.
  - e) Risks to Subjects: Risks to subjects that participate in the survey are minimal. Responses to survey questions will not be associated with individuals and will be kept confidential. Only the principal investigator and student researcher will have access to completed surveys.
  - f) Informed consent: All subjects are self-selected to volunteer to participate in the survey. No adverse action is taken against those who do not choose to participate. Subjects are made aware of the nature and purpose of the research, sponsors of the research, and disposition of the survey results. Signed consent documents will not be collected. Subjects will be given the opportunity to ask questions prior to participating in the survey.
4. If you have any questions about this request, please contact Lt Col Jeffrey Parr (primary investigator) – Phone 785-3636, ext. 4709; E-mail – jeffrey.parr@afit.edu.

Jeffrey C. Parr, PhD, Lt Col, USAF  
Principal Investigator

Attachments:

1. Survey questions
2. Page-IRB CITI Course Completion Certificate
3. Parr-IRB CITI Course Completion Certificate
4. Page-Verbal Statement for Participants
5. Parr-Vita
6. Page-Vita

**Figure A-3. IRB Memorandum for Exemption (cont.)**

#### Verbal Statement for Participants

Hello, I am Capt Will Page. I am a Masters Student at the Air Force Institute of Technology. I am conducting research in collaboration with my advisor, Lt Col Parr. You are being asked to participate in a short survey on the applicability of 3D printing technology within an operational squadron. Participation in the survey is voluntary, anonymous, and there is no penalty for non-participation. If you choose to participate in the survey, no PII will be collected. I will hand out the survey forms and you can choose to participate after looking over the survey content. There are several assumptions that need to be mentioned prior to starting the survey. This survey is focused on validating the potential use of 3D printing technology to solve current operational problems within a squadron. Those participating in the survey need to have a working understanding of the original problem, as well as the problem solution using the 3D printed part. Please indicate whether the printed part actually solved the problem or made it more difficult to accomplish the mission. Please let me know if you have any questions at this time. Thank you for your time.

**Figure A-4. Verbal Statement for Participants**

### Informed Consent

Researcher: Capt William L. Page

Research Advisor: Lt Col Jeffrey C. Parr

You are being asked to participate in a short survey. This survey is part of research examining the applicability of 3D printing technology across the Air Force. Please answer the questions on pages 2 and 3 according to your personal experiences and body of knowledge on the 3D printed part and the problem it was designed to solve. This should take approximately 5-10 minutes of your time.

This survey is the final phase of a plan to identify, design, print, and validate the need for a 3D printer. Your participation in this survey is voluntary. You may leave any question blank that you do not feel comfortable answering. There is no penalty for non-participation and no anticipated risks are associated with participation.

No personally identifiable information (PII) will be collected. The only demographic information that is being requested, should you choose to participate, is number of years of service and your AFSC.

Printed Part Name/Description:

---

AFSC: 

---

Number of years of Service: 

---

#### 1) Quality

##### a. Overall reaction to the new tool/part

i. Useless 0 1 2 3 4 5 6 7 Useful

ii. Difficult 0 1 2 3 4 5 6 7 Easy

iii. Fragile 0 1 2 3 4 5 6 7 Durable

#### 2) Effective to use (effectiveness)

##### a. For its desired purpose, the size of the printed part is \_\_\_\_\_:

i. A Hindrance 0 1 2 3 4 5 6 7 Optimal

##### b. The installation of the part is \_\_\_\_\_:

i. Easy 0 1 2 3 4 5 6 7 Difficult

##### c. The printed part could be effectively used in \_\_\_\_\_:

i. Training Only 0 1 2 3 4 5 6 7 Fully Operational Uses

---

**Figure A-5. User-Centered Usability Survey**

- d. Iterative testing process \_\_\_\_\_ additional unforeseen problems  
 i. Created 0 1 2 3 4 5 6 7 Solved
- 3) Efficient to use (efficiency)
- a. Compared to original process, the new tool makes the process:  
 i. Less efficient 0 1 2 3 4 5 6 7 More efficient
- b. Due to the part being printed, \_\_\_\_\_ specialized tools are needed for installation:  
 i. Several 0 1 2 3 4 5 6 7 None
- c. Tasks when using the tool can be performed in a straight-forward manner:  
 i. Never 1 2 3 4 5 6 7 Always
- 4) Safe to use (safety)
- a. Overall safety of product:  
 i. Dangerous 0 1 2 3 4 5 6 7 Safe to Use
- 5) Having good utility (utility)
- a. Aside from the primary purpose, there are \_\_\_\_\_ other possible uses for tool:  
 i. No 0 1 2 3 4 5 6 7 Multiple
- b. At home station, \_\_\_\_\_ other uses within your flight exist for 3D printed solutions to improve operations:  
 i. None 0 1 2 3 4 5 6 7 Multiple uses exist
- c. In deployed environment, \_\_\_\_\_ other uses within your flight exist for 3D printed solutions to improve operations:  
 i. None 0 1 2 3 4 5 6 7 Multiple uses exist
- 6) Easy to learn (learnability)
- a. Learning to use the tool was:  
 i. Difficult 1 2 3 4 5 6 7 Easy
- b. Discovering additional uses for the tool is \_\_\_\_\_:  
 i. Difficult 1 2 3 4 5 6 7 Easy
- c. A \_\_\_\_\_ amount of Supplemental Reading/Training Required prior to using the tool:  
 i. Time Intensive 0 1 2 3 4 5 6 7 minimal
- 7) Easy to remember how to use (memorability)

**Figure A-6. User-Centered Usability Survey (cont.)**

a. Retraining needs to be done \_\_\_\_\_ to stay proficient on the tool:

i. Often 0 1 2 3 4 5 6 7 Never

b. Advanced technical skills required to use the tool:

i. Expert 0 1 2 3 4 5 6 7 Basic

8) Topology Optimization

a. The addition of topology optimization added \_\_\_\_\_ value to the print:

i. None 0 1 2 3 4 5 6 7 A Lot      N/A

b. What were your impressions of the optimized part?

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**Figure A-7. User-Centered Usability Survey (cont.)**

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## **Vita**

Captain William Page, an officer in the United States Air Force, completed his Bachelor of Science degree in Civil Engineering and received his United States Air Force Commission from The United States Air Force Academy in May 2011. Captain Page's first Air Force assignment was at Tyndall AFB, FL, where he worked as a Readiness Support Officer, Operations Support Officer, SABER Project Manager, Project Programmer, and Chief of Operations and Maintenance Construction (deployed). In 2015, he entered the Graduate School of Engineering and Management at AFIT, where he is currently earning a Master's degree in Engineering Management. His follow-on assignment is to Ellsworth AFB, SD. Captain William Page can be contacted at: [william.page.12@us.af.mil](mailto:william.page.12@us.af.mil).

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14. ABSTRACT  This research explored the application of Additive Manufacturing (AM) to operations for various career fields using case study analysis to investigate to what degree can AM and topology optimization, a mathematical model to optimize the shape of a design, be utilized by various Air Force squadrons in everyday and contingency operations; to what degree can topology optimization be applied to the tools and jigs developed; and how much could topology optimization potentially save the Air Force over a given amount of time? These case studies evaluated nine tools and jigs for Explosive Ordnance Disposal and the Engineering Management Laboratory at the Air Force Institute of Technology. If deemed appropriate by the customer and designer, topology optimization was applied. As the hallmark of a good tool or jig is its usability, a survey was given to rate different aspects of usability for each case study. The scores were then used to identify trends between the case studies. Overall, this research found that AM and topology optimization could be applied to both daily and contingency operations, that topology optimization could be applied to various tools and jigs, and that the application of topology optimization could bring significant cost savings over time.						
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